Synthetic Aperture Radar White Paper 04-20-03

Executive Summary

This white paper examines some of the many operational and developing applications that are possible with satellite-based Synthetic Aperture Radar (SAR). Many of these applications provide significant returns on investment by providing new and more effective means for the Federal agencies to carry out their missions. SAR imagery presently is used by the National Oceanic and Atmospheric Administration (NOAA), the US Geological Survey (USGS), the Federal Emergency Management Agency (FEMA), the U. S. Army Corps of Engineers (USACE), the National Science Foundation (NSF), the National Aeronautics and Space Administration (NASA), and other civilian and Department of Defense (DoD) agencies. Although the U. S. pioneered the development of spaceborne SAR sensors, the U.S. is at present totally dependent on SAR data from satellites launched by other countries. There have been instances where our Federal agencies could not obtain time-critical SAR data for disaster management or other acute needs. The use of SAR by the Federal agencies in response to natural and technological disasters has been weakened by the lack of a US SAR program. The U. S. will greatly benefit from a national system and a robust program for the development, deployment, and validation of new SAR technology and the broad and open distribution of SAR data.

Introduction

Synthetic Aperture Radar (SAR) is an essential tool in the national effort to improve the health and security of our nation's citizens and our natural resources, and to protect our environment and our commerce. Federal agencies are increasingly turning to SAR both for all-weather remote sensing imagery and as a technique to precisely detect and define changes of the Earth's surface. The National Oceanic and Atmospheric Administration (NOAA) relies upon SAR imagery to track sea ice cover and iceberg locations for the safe navigation of our maritime vessels. The National Aeronautics and Space Administration (NASA) and the National Imagery and Mapping Agency (NIMA) used a SAR carried aboard the Space Shuttle to precisely map the Earth's surface topography with significant benefits to our nation's security. The U.S. Geological Survey (USGS) uses SAR to measure the activity of awakening volcanoes, which threaten our cities and air traffic routes, to measure land movements produced by large earthquakes, and to monitor the supplies of ground water stored beneath thirsty cities. To develop and extend our ability to warn of impending natural hazards, the National Research Council, NSF, NASA and the USGS endorse a proposal for a US Interoferometric SAR (InSAR) satellite mission as one of four principal instruments of EarthScope Program. EarthScope, an initiative of NSF's Major Research Equipment (MRE) program, is comprised of four observatories to reveal the workings of the Earth's interior much as telescopes have revealed the heavens. Three of these observatories, the continent scale seismic and GPS arrays and the instrumented drilling of the San Andreas Fault received an initial appropriation from Congress in fiscal year 2003. The fourth observatory, a space based SAR mapping system remains unfunded. There is however a significant and growing consensus within the Federal agencies that we need a national program to develop a space-borne Synthetic Aperture Radar observing system to meet this nation's operational and research needs.

Although the U.S. launched Seasat in 1978 (the first space-borne SAR), we are nowadays totally dependent upon the space programs of other countries for access to these critical remote sensing data. The Subcommittee on Disaster Reduction (SDR) believes that the benefits of a national SAR program to the US and the world are clear and highly significant. The single most important benefit of a US SAR program will be the ability to focus SAR resources upon high-priority US targets. Federal agencies with mission requirements involving natural hazards and resources regard assured access to high quality SAR data as an essential tool to meet their mandates. The scientific and educational benefits of a robust civilian SAR program are also substantial. A US national program for the development, deployment, and validation of new SAR technology and the availability of routine near-real time SAR data products to the Federal and research communities will encourage the growth of a vibrant commercial remote sensing industry. Most of all, it will enhance the security and well being of our citizens through more effective forecasts of natural hazards and improved assessments of our natural resources.

The Technology……

The present utility and future promise of SAR stems from its all-weather day and night operational capability and from numerous and innovative observing strategies. These new measurement strategies combine radar images of the Earth's surface using different radio frequencies and geometries of observation. A SAR measures the distance from the observing satellite to a reflection point on the ground. Utilizing the reflected signal's amplitude and phase gives a very sensitive measurement of the nature of the reflecting surface. Modern SAR satellites precisely measure thousands of square miles in a very few minutes. The resolution of the technique is a function of the wavelength and bandwidth of the signal and the sensitivity and the power of the satellite system. SAR data can be acquired with great reliability to enable precision monitoring of surface processes. For example, by combining SAR images taken at different times, differences in land surface elevation due to the pumping of underground water or oil, or the intrusion of new magma beneath a volcano can be measured to a few millimeters (less than half an inch) over hundreds of square miles --- and this level of detail can be resolved from satellites several hundreds of miles away.

During the past two decades, space geodetic techniques, such as geodetic GPS measured the position of permanent monuments with millimeter precision over the course of months and years. Changes to the Earth's surface revealed by these serial point measurements led to a new understanding of the deformation of the Earth's surface caused by forces both natural and man made. Geodetic imaging is a revolutionary new technique, which complements geodetic point positioning with measurements over large areas rather than single points. Geodetic imaging, using Interoferometric SAR (InSAR), provides accurate topography while resolving changes in the land surface with millimeter accuracy. InSAR measures the difference in radar signal phase and amplitude between two or more carefully positioned SAR images for the same area. The holographic differencing reveals the changes in the Earth's surface which occurred between the capture of two radar images with resolution of a fraction of the short radar wavelength. As an added benifit, new research efforts are now successfully focusing upon the utility of resolving the polarization (i.e. horizontal or vertical) of the radar signals to resolve surface characteristics. Geodetic imaging has captured the enthusiasm of the scientific community because it provides high resolution regional views of changes in the Earth's surface which spans both space and time. Though not without its technical challenges, InSAR based geodetic imaging is synoptic, intuitive, and effective. InSAR based change detection is an extremely effective complement to ground based GPS and seismic instrumentation. InSAR based geodetic imaging offers new promise in the forecasting of volcanic eruptions, earthquakes, landslides, the direct measurement of erosion, the motion of ice streams and glacial retreat, and other yet undetected forces which change the Earth's surface.

……. and its Application to Science and Society

The specific benefits of a national space based SAR program can be grouped into several application areas. These groups are by no means all encompassing but represent specific areas identified by the SDR as immediate and obvious targets for a national program.

Earthquake Hazards

The most challenging goal for InSAR is mapping slow Earth deformation. This includes the interseismic accumulation of strain leading up to earthquakes, as well as transient post-seismic strain relaxation following earthquakes. Scientists supported by NASA, the USGS, and the NSF are seeking repeated measurement of surface change in seismically active areas along the Earth's plate boundaries where the highest probability of earthquakes exists..From this new knowledge will come better estimates of earthquake hazards. In addition since earthquakes deform adjacent land which in turn lead to new earthquakes in other regions, the InSAR would be able to follow this deformation which could lead to a predictor of future earthquake areas The scientific community and the National Research Council have repeatedly endorsed the use of InSAR to advance our understanding of the earthquake cycle. InSAR is a space geodetic imaging technology, which enables the precise measurement of surface deformation over large regions before, during, and after earthquakes. InSAR observations are leading to a revolutionary change in our understanding of the slow changes in the Earth surface that build the forces released in earthquakes.

SAR can also serve in earthquake disaster response by providing regional high-resolution information for the assessment of both risk and damage to critical infrastructure such as buildings, dams, aqueducts, highways, bridges, sewer and gas lines. This SAR based all weather damage assessment capability will complement information available from local observing systems such as leak detectors, strong motion seismic networks, or emergency response teams.

Volcanic Hazards

Interferometric analysis of multiple SAR images of volcanoes revealed that a number of U.S. volcanoes previously thought to be dormant or inactive are in fact actively changing shape in response to the movement of magma and gases beneath the volcano. Sequences of InSAR images for Etna (in Italy) and Okmok and Westdahl (in Alaska) dramatically demonstrate the inflation of the volcano's surface preceding an eruption. The predictive potential of these images is clear. InSAR data provides an important new capability to define both the long term and near term risk to our citizens and our infrastructure from volcanic hazard. Combined with ground-based seismic, GPS, and gas monitoring, InSAR data would provide important new remote warning capabilities to help mitigate disasters such as the 2002 loss of 147 lives and 12,000 homes to the sudden fissure eruptions at Nyiragongo Volcano in the Democratic Republic of Congo or the 1985 lahars which claimed approximately 23,000 lives in the village of Armero, at the foot of Nevada del Ruiz Volcano, Colombia. There are the more than 100 potentially violent volcanoes along the air routes from the US to eastern Asia. The addition of all weather InSAR measurement of the Aleutian, Kamchatkan, and Kurile volcanic chains to the existing monitoring from weather satellites and ground-based instruments will further reduce risk of eruptions and volcanic ash clouds to our aircraft which fly these busy North Pacific jet routes.

Flooding, Severe Storms, and Resource Management

InSAR is an effective tool in the mapping of snow pack, the accurate measurement of water level changes in river valleys and wetlands, the estimation of soil moisture and the delineation of topography for catchment basins and flood plains. All weather SAR images can track rising flood waters in support of responding to flood disasters and to flood mitigation efforts. Post-flood images can be used to assist in quantitative damage assessment, and for rapid damage assessment during the immediate post-flood period when the area may still be cloud covered.

SAR images can also serve in rapid damage assessment after major hurricanes, when cloud cover and damaged infrastructure (telephones, roads, bridges) make conventional surveys difficult. Sequences of InSAR images could detect weakness in the overburden in landslide-prone areas as an early sign of incipient ground failure. InSAR will also measure surface change caused by human activity. Uncontrolled subsidence can lead to higher flood potential and other risks to infrastructure. Land erosion carries away significant amounts of precious topsoil and chokes our rivers and coastal zones. High precision SAR generated topographic maps would identify with great precision those regions which are loosing soil due to erosion.

Water Resource Management

SAR is beginning to demonstrate its utility in the management of water resources. Certainly the timely and uniform measurement of mountain snow pack and glacier dynamics is as important to water resource management as it is to disaster mitigation.

InSAR has demonstrated its ability to measure surface subsidence and rebound in response to aquifer discharge and recharge in regions such as Los Angeles, Las Vegas, Houston and other cities dependent upon subsurface water. The USGS and NASA are investing significantly in the development of SAR technology to advance the remote measurement of land subsidence as a proxy for aquifer charge.

Soil moisture is an environmental descriptor that integrates much of the land surface hydrology and is the interface for interaction between the solid Earth surface and life. As central as this seems to the human existence and biogeochemical cycles, soil moisture has seen little application in land process models because soil moisture is difficult to measure on a consistent and comprehensive regional basis. Point measurements have very little meaning because soil moisture exhibits very large spatial and temporal variability. Therefore it has been impractical to include soil moisture in current hydrologic, climatic, agricultural, biogeochemical, or fire hazard models despite the acknowledged importance of these measurements. Frequent and accurate synoptic measurement of soil moisture is the single most significant weather-related variable needed by USGS and NOAA to advance the science of forecasting rainfall-induced landslides. These landslides take place when soil moisture exceeds critical thresholds, and result in a large proportion of the $2 billion annual direct landslide losses in the United States, especially in El Nino years. Polarimetric SAR imaging of large areas may be successfully applied to the measurement of soil moisure. Soil moisture variations change the ground surface conductivity and therefore the characteristics of reflected SAR signals. Polarimetric SAR would be used to separate the effects of changes in soil moisture from changes in biomass and surface roughness.

Satellite imaging in the visible portion of the spectrum is widely used to map extent of snow-cover. Snow cover data are incorporated into operational snowmelt forecasting schemes, but the snow-covered area may not be a reliable indicator of the amount of water stored in the snow pack. A fundamental property of snow required for the forecasting of water supply is the snow-water equivalence, which is the amount of water that can be obtained from the melted snow. Traditionally this variable is measured at several hundred snow courses throughout the mountainous regions of the western U.S. This measurement is of limited value. There is a need to develop a higher resolution estimate for the spatial distribution of snow-water equivalence over entire basins. The measurement water equivalence in snow pack could be done with dual-polarization L-band SAR data to estimate snow density and higher frequency SAR data to estimate snow volume.

With more accurate estimates of snow volume, detection of melting snow, and the measurement of the spatial distribution of snow-water equivalence, wewould be able to better forecast melt on short and season-long time scales. Such forecasts would improve the management of reservoirs in areas of snowmelt runoff, and thus improve the allocation of water for agriculture and other uses.

Cryospheric Hazards

All-weather SAR imaging of the high latitude seas provides information which is vital to minimizing the hazard and cost of sea ice in maritime activities. Monitoring sea ice also provides important information on climate trends such as the reported interannual loss of ice cover in the Arctic Ocean. Airborne tracking of icebergs and ice cover is expensive, risky, and limited in scope due to weather, range, and budgets. Satellite ice tracking utilizing SAR imagery has been amply demonstrated and is quickly becoming the accepted technique. The National Ice Center, a multi-agency operational center representing the Navy, NOAA, and the Coast Guard, does not have a U.S. source for its required data, and is now totally reliantupon Canadian and European SAR satellites for its radar data.

Sustained development of coastal areas worldwide has made the global economy extremely vulnerable to changes in sea level. Ice sheets and mountain glaciers contain a frozen reservoir totaling nearly 80% of the world's fresh water and are the primary source of future sea level rise. A U.S. InSAR, would be an important new tool to precisely measure the volume and dynamics of our glaciers and ice caps though they are often shrouded in clouds. The radar techniques applied are very similar to those used in the measurement of land topography and the motion along faults as described earlier.

Surface topography determines the magnitude and direction of the gravitational force driving the ice flow. Therefore the detailed topography of the ice sheet determines the boundaries of individual drainage basins contained within the ice sheet. In addition, the undulating character of the ice-sheet surface provides proxy evidence for whether the ice flow is dominated by ice sliding over a well-lubricated bed, or whether the ice is frozen to the subglacial terrain. Finally, the complete elevation field would be an invaluable aid to the interpolation of laser altimetry which inherently only measures elevations along very narrow corridors across the ice sheet.

Ice velocity is the fundamental parameter representing the dynamics of ice. It can be compared with "balance" velocities determined from areal integration of the snow accumulation to assess the state of equilibrium of any ice mass, or portion of an ice mass. Even in the absence of accumulation data, the magnitude and direction of ice flow is critical input to dynamic models of ice flow and, when compared with surface topography, it identifies regions that are far from equilibrium.

SAR holds the advantage of viewing through clouds--frequently persistent at the edges of ice sheets and in mountainous terrain. The InSAR technique is building an unprecedented series of snapshots documenting the short-term evolution of the ice sheet. This objective is particularly germane given the recent and unexpected disintegration of large portions of ice shelves in the Antarctic Peninsula and the implied consequences of climate change to coastal communities. Using the Canadian RADARSAT-1, NASA is periodically imaging the entire Greenland and Antarctic Ice Sheets.

The high resolution and cloud-penetration capabilities of SAR have made it a particularly useful tool in monitoring spring breakup of major rivers in northern regions (e.g., Yukon in Alaska and Yellowstone in Montana). Onset of breakup, ice runs, ice jams, and flooding due to ice jams have all been monitored with ERS-2 and RADARSAT-1 SAR imagery.

Forests and Agriculture

The all weather capability of SAR imaging offers great promise for the measurement of biomass or fuel load in the management of fire hazard and as an automated technique in support of fire fighting and controlled burns. Polarimetric InSAR is being used to develop operational approaches for addressing patterns of deforestation and forest regrowth, and their contribution to the global carbon budget. Polarimetric SAR techniques would be used to estimate biomass because the signals change polarization as the bounce between ground and the overlying vegetation. Unfortunately, the dearth of SAR data has impeded its development as a wide area surveying technique.

Wildfire is a major cause of property loss and habitat degradation. The sensitivity of SAR data to above-ground biomass would be used to improve estimation of the available fuel loads and could prove useful in developing strategies to reduce risk through management practices such as thinning. In addition, SAR data could be used to enhance the assessment of wildfire risk and the impact of wildfire on subsequent erosion and landslides. Studies in Alaska have taken advantage of the sensitivity of SAR to the dryness of the fuel load and thereby improve on traditional methods based solely upon weather stations to provide spatially explicit mapping of fire hazard. Such products would be of great value to the allocation of fire fighting resources.

Land cover change is one of the fundamental factors in resolving the global carbon cycle. In addition to identifying primary land conversion, successful efforts are underway using SAR to estimate regrowth in secondary forests, a key factor in carbon balances. These efforts would allow the measurement of forest regeneration in the worldwide belts of tropical, temperate, and boreal forest at yearly intervals over at least a three-year period.

Notwithstanding the burning of fossil fuels, worldwide deforestation and afforestation practices are believed to have the highest impact on the net flux of greenhouse gases and carbon management. Since carbon is stored in the form of biomass in forests, which is interdependent with factors such as nutrient fluxes, water availability, age of forest, and temperature, monitoring the changes in biomass provides a critical piece of information in understanding the global carbon cycle. An L band polarimetric InSAR would greatly assist in this area.

Ocean and Coastal Zone Observations

SAR observations of the oceans contain large amounts of information on both coastal and deep-ocean physical processes important to weather forecasting, the management of marine resources, pollution control, and safety of navigation.

SAR images display signatures that discriminate important air/sea interaction processes due to sensitivity to small-scale surface roughness. Although the roughness modulations are often small (of the order of the radar wavelength, i.e., several centimeters), they nevertheless are quite apparent in the imagery and often mirror significant and extensive ocean as well as atmospheric dynamics. For example, it is the interaction between the planetary boundary layer of the atmosphere and the upper ocean that establishes the interchange of heat, momentum, and moisture in both the lower and upper atmospheric. It is those fluxes that must be determined if we are to understand and introduce into our weather prediction models the ability to better predict air temperature, humidity and cloudiness as well as the longer term effects of carbon dioxide sequestration.

Much, if not most of the air/sea interchange occurs episodically during storms and high-wind events. During these events, the surface of the sea is hidden from remote sensors operating in the visible and infrared portions of the electromagnetic spectrum because of cloud cover. Furthermore, ship and buoy-based measurements are more limited or even compromised during such heavy weather episodes. Thus, it is not possible to make accurate *in-situ* observations during those times when energy transfer is most active. It is at these times that spaceborne SAR provides views of the sea surface that are difficult to obtain by any other means. SAR imagery has proven its utility in locating small severe storms like polar mesoscale cyclones which can have winds of hurricane force, but which occur in regions with little *in situ* data and obscured from visible/IR satellite sensors by clouds. SAR imagery penetrates the clouds to show the location of the center of the storm at the sea surface, the position of high-wind fronts, swell direction and wavelength, and the general morphology and extent of the storm. If the storm is not obscured by a solid deck of clouds, then the SAR imagery of wind patterns at the ocean's surface nicely complements information on winds and fronts at the top of the clouds derived from visible/IR sensors. Recently, SAR imagery as been employed in hurricane studies of eye morphology, location of rain bands, convection cells, high-resolution wind patterns, and roll vortices.

The most important SAR characteristics for oceanography are all weather operation, wide swath measurement, dual polarization capability, and daily to weekly observation schedules. Both open-ocean and coastal observations are desired. Coastal zone observations are especially desired because the highly dynamic region between the coast and the edge of the continental shelf is critical to many facets of our society such as the coastal infrastructure, fishing, boating, shipping, and offshore oil interests.

In coastal regions, NOAA has demonstrated the utility of SAR as a means of monitoring and alerting maritime traffic and low-flying aircraft to strong wind events such as gap winds, downslope winds, and barrier jets. Imaging SAR instruments are unique in their ability to measure winds right up to the coast and even in bays, rivers, and lakes. There is no contamination of the signal by adjacent land such as occurs in scatterometer and passive microwave instruments. Others have demonstrated the application of along track SAR interferometry in the measurement of coastal currents (an application important for search and rescue, fishing, and marine transportation). SAR has also amply demonstrated its ability to detect and track both anthropogenic and natural oil slicks. This ability is especially useful in the enforcement of pollution laws because SAR can monitor dumping day and night during a wide range of weather conditions. This is a critical capability since most large oil spills at sea occur as a result of severe weather. Oil slick tracking is also of great importance in the containment of oil spills. Winds derived from SAR can provide local wind conditions for use in oil spill trajectory models.. Norway has demonstrated the operational usefulness of SAR imagery for the monitoring of illegal oil dumping and bilge pumping from vessels underway. SAR has also demonstrated its utility in the detection of vessels at sea for the enforcement of national maritime borders, exclusive economic zones and fishing regulations. Violation of environmental and resource regulations often occur in cloud covered condition far from land when enforcement capability and optical tracking are least effective. Using SAR along with Vessel Monitoring Systems which report the location of licensed fishing vessels would allow enforcement agencies to discriminate between legal and illegal vessels.

Summary

There is clearly a growing need for access to SAR data by the U.S. civilian agencies whose mandate is the security and protection of our nation, its resources, infrastructure, and commerce. In most cases existing applications would greatly benefit from a viable and sustained research and development effort aimed at improving economy of operation and the development of new SAR applications with high potential pay back. In some cases such as ice monitoring, land surface change detection, volcano monitoring, topographic measurement, coastal winds, and oil spill response SAR technology has been well demonstrated. Further research will only strengthen rationale for SAR. SAR satellites are relatively expensive instruments but as we have seen, the applications of this technology are broadly based and will lead to a significant reduction in the loss of life and damage to property as well as improved efficiency and opportunity.

Table 1. Examples of SAR Applications

Geophysical parameters		**Algorithms and mission parameters**	**Maturity** (i.e. readiness for "operational" use)
Surface deformation		Repeat-pass interferometry within 1 month; L-band; orbit control	Validated (line-of-sight) Demonstrated (vector)
	Pre-seismic	Multiple repeats (noise identification & reduction)	Research
	Co-seismic	Pre- and post- coverage	Validated
	Post-seismic	Targeted coverage	Validated
	Inter-seismic	Extended regional areal coverage (100s km) at low-resolution (25m); long time series (yr), regular repeats (mo).	Demonstrated (creep zones) Research (other areas)
	Pre-eruptive	Multiple repeats (noise identification and reduction)	Research
	Co-eruptive	Targeted coverage	Validated
	Inter-eruptive	Long time series. Regular repeats.	Demonstrated
	Landslides	Local coverage, high resolution.	Demonstrated
	Subsidence	Regional & local coverage	Demonstrated
Other geometrical surface changes (e.g., lava flow)		Long time series; Regular repeats; L-band	Demonstrated
Glacier & ice sheet velocity	*Ice sheets*	L-Band repeat-pass interferometry within 8 days at latitude > 658	Demonstrated (L-band) Validated (C-band)
	Glaciers	Repeat-pass interferometry (1-2 days?) or pattern matching	Demonstrated
Glacier volume & topography		L-Band repeat-pass interferometry within 8 days	Demonstrated
Forest biomass	*Boreal*	L-band HV	Demonstrated
	Temperate	L-band HV	Demonstrated
Vegetation Classification	*Forest*	L-band dual pol.	Research
	Crops	L-band quad pol.	Research
Aerodynamic roughness		L-band HV	Demonstrated
Vegetation Moisture		L-dual pol., or C-dual pol. (+ species type ancillary)	Research
Soil moisture	*Bare*	L-band quad-pol.	Demonstrated
	Grass and shrubs	L-band quad-pol.	Research
	Forest	P-band quad-pol.	Research
Snow density		L – Quad pol.	Research
	Water equivalence	Density from L – Quad pol. + depth from higher frequency	Research
Inundation and extent (floods)	*Forests*	L-band HH	Demonstrated
Oceans	*Ice type*	L-band quad-pol.	Demonstrated
	Mesoscale circulation	L-band quad-pol.	Research